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# Solar Energy

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16. Abstract

The use of solar energy, the techniques to be employed, and future prospects of solar energy as a widespread energy source are discussed. Diagrams of solar power systems are presented.

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# SOLAR ENERGY

Takashi Horigome and Tatsuo Tani

The current world-wide energy crisis originated because of the uncertainty of the oil supply, and brought an end to the age of a cheap and stable energy supply. It forced mankind to realize the finiteness of the energy resources. /47*

Furthermore, the accelerating increase in energy consumption of modern society has caused serious environmental pollution, and has already had a bad effect on human health and ecology.

For the steady progress of human society, it is necessary to save the existing energy resources, and find out ways to prevent pollution, and also restructure industry in order to save energy. Moreover, it is important to develop new energy resources to replace existing energy sources and to diversify energy sources. To meet the situation, new technologies consuming less energy and the research and development of new energy sources are required. Development of new energy resources is not only a positive measure for overcoming the current energy crisis, but also indispensable for assuring the steady progress of human society in the future.

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*Numbers in the margin indicate pagination in the original foreign text.

As candidates for new energy resources, there are solar energy, ocean energy, wind energy, nuclear energy, etc. However, only thermal energy from controlled fusion reactors and solar energy are expected to meet future energy demands. Even though research and development for controlled nuclear fusion has been in progress for many years, there are still too many problems to be solved. However, solar energy has better prospects. It is practically limitless, pollution free, and has zero cost, so that once tapped it will contribute greatly to improving the energy situation.

In the following, we will discuss solar energy, its utilization techniques, and future prospects.

The sun is a gaseous sphere at high temperature located at the center of the solar system, and its energy comes from nuclear reactions described below:

> <u>hydrogen-hydrogen fusion</u> — two hydrogen nuclei collide to form a heavy hydrogen nucleus, then form a helium nucleus;
>
> <u>carbon-nitrogen reaction</u> — carbon nuclei collide with hydrogen nuclei, and become nitrogen and oxygen isotopes; then these form carbon and helium nuclei.

These reactions are caused by the high temperature inside the sun. The hydrogen bomb is based on the same principle. However, a nuclear bomb is a device with an instantaneous nuclear reaction, while the sun sustains nuclear reactions over years and years, practically endlessly. It can be regarded as an eternal, cost-free fusion reactor.

The magnitude of solar radiation is almost the same as that of black body radiation at 6000° C. The total energy over the entire frequency range is called the solar constant (the rate of energy per unit time falling on a unit area placed outside the Earth's atmosphere at the average distance between the Earth and the sun). It is usually assumed as 1.94 or 2.00 cal/cm$^2$/min, or, equivalently, 1.395 kW/m$^2$ $\pm$ 2%. Considering that the Earth's cross section receiving solar energy is $1.275 \cdot 10^{11}$ m$^2$, and ignoring the energy loss due to reflection, we can calculate the solar energy continuously arriving on the Earth as $1.73 \cdot 10^{17}$ kW, or equivalent to $5.5 \cdot 10^{24}$ joules per year. This amounts to one two-billionth of the total annual solar radiation ($1.01 \cdot 10^{34}$ joules). As can easily be seen from the flow of solar energy (see figures on pages 8 and 9*), the density of solar energy available on the ground is approximately 1.0 kW per square meter after correcting for the loss occurring during its penetration through the atmosphere. As a numerical example, the total solar energy available on the ground is about 30,000 times the total energy requirements of the world in 1970. Japan's annual energy consumption was approximately $3.5 \cdot 10^{12}$ kWh in 1970, while the solar energy falling on the entire area of Japan is estimated to be $5.72 \cdot 10^{11}$ kWh. (Average latitude 35°, atmospheric penetration rate 0.7; insolation time per year 2000 hours). Since the ratio is 0.6%, we can get some idea about the magnitude of solar energy.

Moreover, solar energy is different from other energy sources in that it is not only a clean energy source, completely free from air pollution, radioactive pollution, etc., but also it is very attractive when thermal pollution is considered. Thermal pollution (heat balance of the Earth) will be a decisive factor in determining the limit of energy consumption in the future. As a measure of the upper limit of the allowable annual energy consumption, we can think of the total kinetic energy of wind and ocean waves. This amounts to $1.2 \cdot 10^{22}$ joules per year, and is approximately 60 times the present energy consumption of the whole world. This is an indication of the manner in which energy consumption is approaching the upper limit. /48

Solar energy has been contributing to human life since primordial times, and also is being utilized now in various ways, as shown in Table 1. For practical applications, solar power generation and heating/air-conditioning are most important at present.

*Translator's Note: Foreign pages not included in this translation.

TABLE 1. SOLAR ENERGY UTILIZATION. THE ENERGY THAT THE EARTH IS CONTINUOUSLY RECEIVING FROM THE SUN AMOUNTS TO $1.73 \cdot 10^{17}$ WATTS ($5.5 \cdot 10^{24}$ JOULES PER YEAR) AND IS USED IN VARIOUS WAYS AS SHOWN IN THIS FIGURE. THIS FIGURE WAS PREPARED BY MR. TETSUO NOGUCHI WHO IS IN CHARGE OF THE SOLAR FURNACE AT THE NAGOYA INSTITUTE OF INDUSTRIAL RESEARCH (ENERGY, P. 71, 1970).

| | Warm water holder | Solar cell | Distillation | Solar furnace | Greenhouse | Warm pond | Drying station | Salt manufacture | Ice manufacture | Solar power system | Insolation measurement | Cooling facility | Solar engine | Air conditioning | Heat and air conditioning | Water pump | Photo biology | Swimming pool | Air heating | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Australia | o | ⊙ | o | o | ⊙ | | | | | | o | | | | ⊙ | | o | | ⊙ | |
| Burma | ⊙ | | | | | | | ⊙ | ⊙ | | | ⊙ | | | | | | | | ⊙ Cigarette lighter |
| Canada | | ⊙ | ⊙ | | | | ⊙ | | | | | ⊙ | o | ⊙ | | | ⊙ | | | |
| Ceylon | o | | | | | | ⊙ | | ⊙ | | | | | | | ⊙ | | | | |
| Chile | | o | ⊙ | | | | | o | | | ⊙ | | | | | | | | | ⊙ Selective absorption surface |
| England | ⊙ | | | | | | | | | | ⊙ | | | | | | ⊙ | ⊙ | | |
| France | ⊙ | | ⊙ | ⊙ | | | | | | | | | | | o | | o | | | |
| Greece | | | ⊙ | | | | | | | | | | | | | | | | | |
| India | ⊙ | | o | | | | ⊙ | | o | | ⊙ | ⊙ | ⊙ | | o | | | | | ⊙ Melting snow |
| Israel | o | ⊙ | | | ⊙ | o | | | | | ⊙ | | | | | | ⊙ | | | |
| Japan | o | o | | ⊙ | ⊙ | ⊙ | | ⊙ | | o | o | | | | ⊙ | | o | | | o Melting snow |
| Guinea | o | | | | | | ⊙ | ⊙ | | | | | | | | | | | | |
| Hungary | | | | | | | | | | | ⊙ | | | | | | | | | |
| Belgium | | | | | | | | | | | ⊙ | | | | | | | | | |
| Malaysia | o | | | | | | | | | | | | | | | | | | | |
| Senegal | | | | | | | | | | | | | | | | o | | | | |
| Italy | o | | | | | | | | | | | | ⊙ | | | | | | | |
| Russia | o | o | o | ⊙ | | | | | | o | o | | | | o | o | | | | |
| New Zealand | | | | | | | | ⊙ | | | | | | | | | | | | |
| Pakistan | | o | o | | | | | | | | | | | o | | o | | | | |
| U.S.A. | o | ⊙ | ⊙ | o | ⊙ | | o | | ⊙ | ⊙ | ⊙ | o | ⊙ | o | o | | o | | ⊙ | ● Selective absorption surface |

o — nonactive case.

Being a low density energy, and affected by variations due to the day and night cycle, weather and seasonal changes, etc., on the ground, it is quite different from fossil fuels. These are the points to be kept in mind in carrying out research and development of solar energy utilization.

A solar furnace is a kind of optical furnace equipped with a concave mirror or lens to collect solar energy, and heat material placed at the focal point. Reflection mirrors are assembled based on their applications, and can be classified into two main types: direct access types, and heliostat types. The heating material container, loo, and furnace wall do not cause any kind of pollution, and are free of electromagnetic fields. There are variations in the insolation.

Small size solar furnaces with a capacity of 2 to 3 kW are almost exclusively used either in basic research of material properties for high temperature technology or in photosynthesis experiments. France has a large scale solar furnace whose output power capacity is 1000 kW, at Fort-Remeu in the Pyrenees. This furnace is capable of producing 2.5 tons of fireproof material daily.

In Japan, the first solar furnace (direct access type, diameter 3 m), was constructed by the Nagoya Institute of Industrial Research as solar furnace No. 1, in 1954. Then followed solar furnace No. 2, by the same group. Later on, Measurement Laboratory, Tohoku University and the Department of Mechanical Engineering, Keio University, also built their own solar furnace. They are being used for research on the solidification point of high melting metallic oxides, chemical reactions, and phase equillibrium at high temperatures. In particular, the above-mentioned Nagoya group made progress in measurement techniques of test materials at high temperatures to enable them to develop a new instrument for research on material properties at high temperatures (see figure on page 83*). New developments in measurement techniques and advances in knowledge about high temperature properties of materials are expected as the measurement techniques improve.

*Translator's Note: Foreign page not included in translation.

Contrary to the case of France, it is doubtful a solar furnace industry will develop in Japan for domestic and economic reasons. However, solar furnace research still occupies an important position in the research and development plan of solar energy utilization. In Japan, we need basic research in order to develop a large scale solar furnace as a heat source for high temperature industries. /49

A solar energy air-conditioning system which collects the solar energy (50 - 150°C) by means of a heat collector is mainly used for the air-conditioning of residential houses, apartment houses, office buildings, etc. As illustrated in Figure 1, it consists of a heat collector, heat storage unit, auxilliary heat source, and heater/air conditioner. The development of a high efficiency collector is essential for this system. In general, the collector is composed of two pieces of glass plates through which solar heat reaches the absorber unit (black metallic plate).

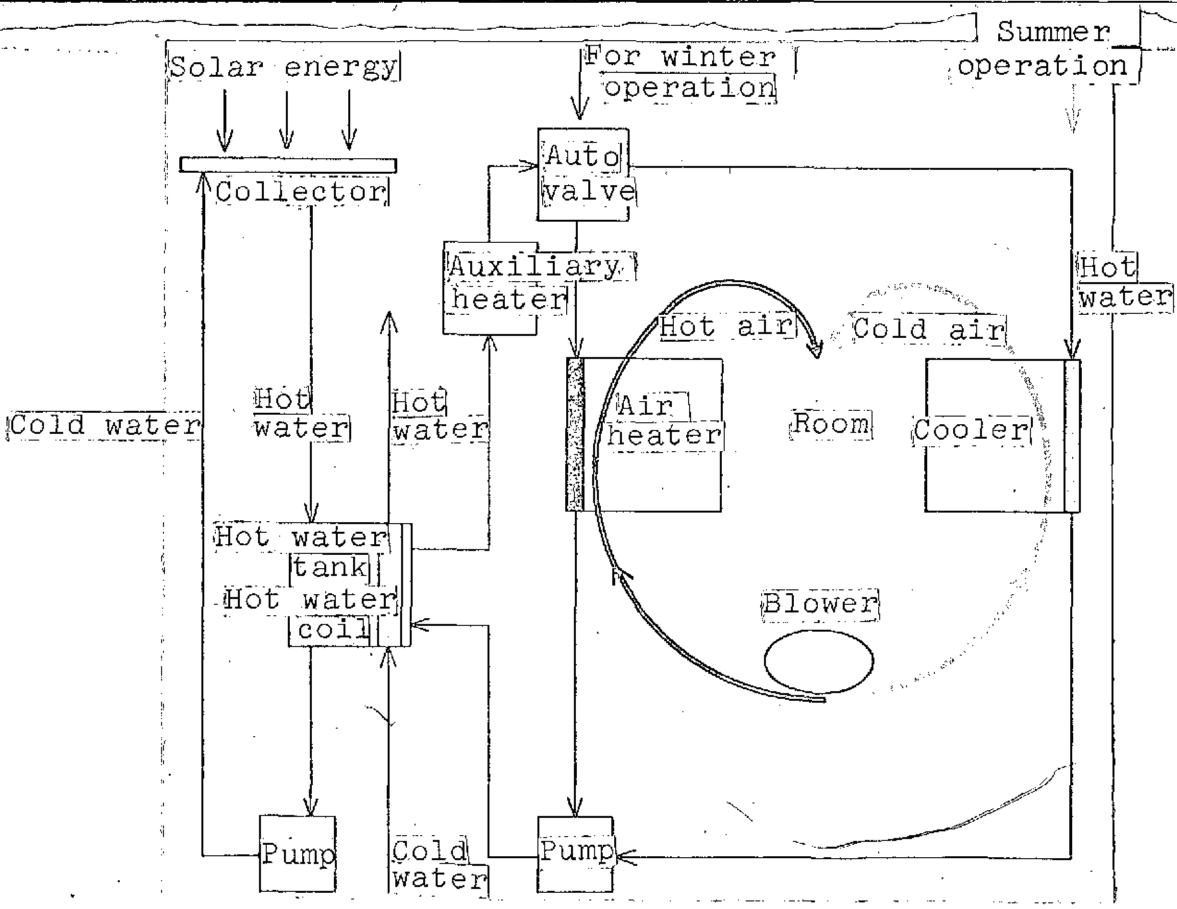



Figure 1. Solar energy heating/air-conditioning system. Heating and air conditioning is done by using solar energy. High efficiency collector is a most important factor

Recently, new types of collectors have been introduced, such as the selective absorption surface type, honey comb structure type, etc. A new type of collector developed at the University of Delaware is equipped with solar cells within the collector, so that it is possible to have heat and electricity at the same time. Since temperatures involved are low, water is being used as the heat transfer and storage medium, but alternative media are being sought.

At present, the solar heating/air-conditioning system is either at the experimental stage or used together with the existing systems. However, we will find this system in practical use in the near future. For the further development of this system, we need higher efficiency heat collectors, a storage system, a refrigerator for the solar energy air conditioner, and a design for the optimal system.

Basic research, technical development, system design, economic evaluation, system test and test run will be performed.

Next let us consider solar power systems. They can be classified as solar cell power systems and solar heat power systems. Solar heat power systems convert solar heat into electrical energy. Its main parts are the collector, storage unit, and heat exchanger. A solar light power system converts solar energy directly into /50
electrical energy using a photoelectric transducer, such as a solar cell. We shall explain these power systems below.

Figure 2 is a diagram of a multipurpose solar energy utilization system. This system stores solar energy in the form of heat or hydrogen gas, which is easily stored.

Figure 3 shows a solar heat power system as a combination of a heat collector system, heat transfer and storage system, heat exchanger, and generator system.

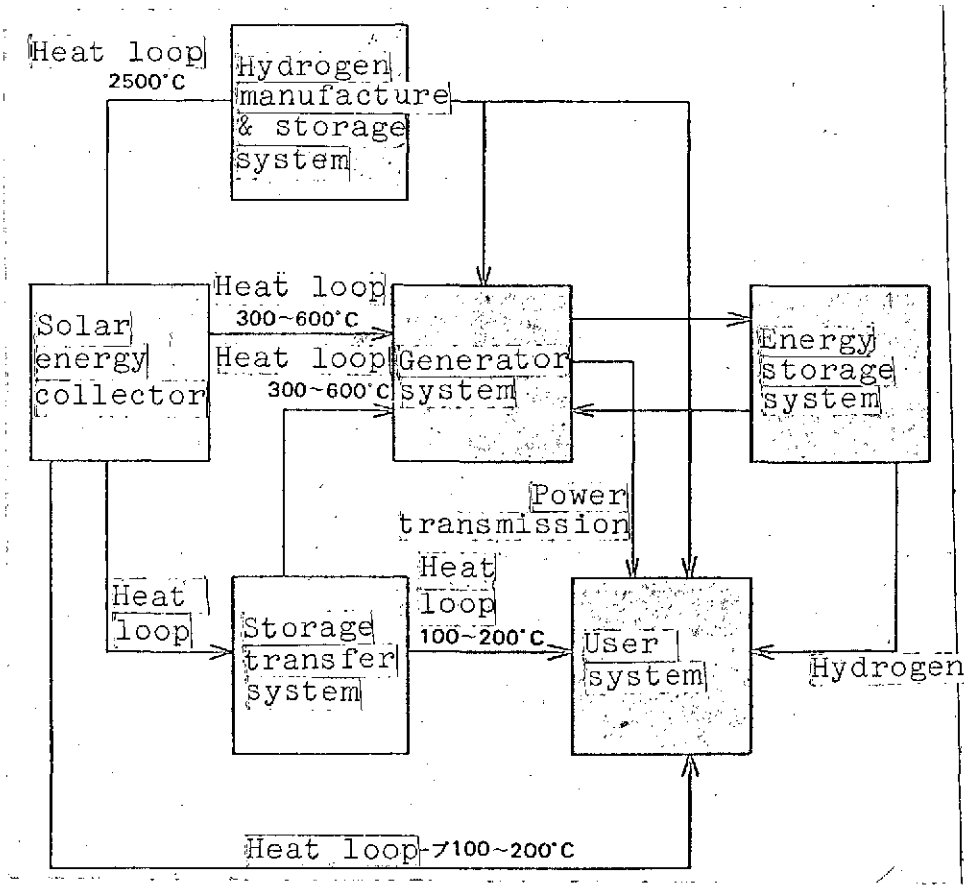



Figure 2. Solar energy utilization system on the ground. This is multipurpose solar energy utilization system. Solar power system is shown in Figure 3

First, solar heat is absorbed and converted by the collector system, then stored in a heat transfer loop (high temperature heat loop, or heat pipe) before being transferred to the storage unit of the heat exchanger system. Finally, it is supplied to the generator system through various heat transfer loops.

Figure 5 shows the model solar power system built by the authors. The absorption capsule is placed at the focus of the parabolic mirror (collector area, 1.2 $m^2$). Collected solar energy (collection rate : 65) is sealed inside the absorption capsule by a selective transmission membrane, then captured by an absorber placed at the center of the capsule, and then transferred to the heat exchanger through the heat transfer medium. The selective transmission membrane and the selective

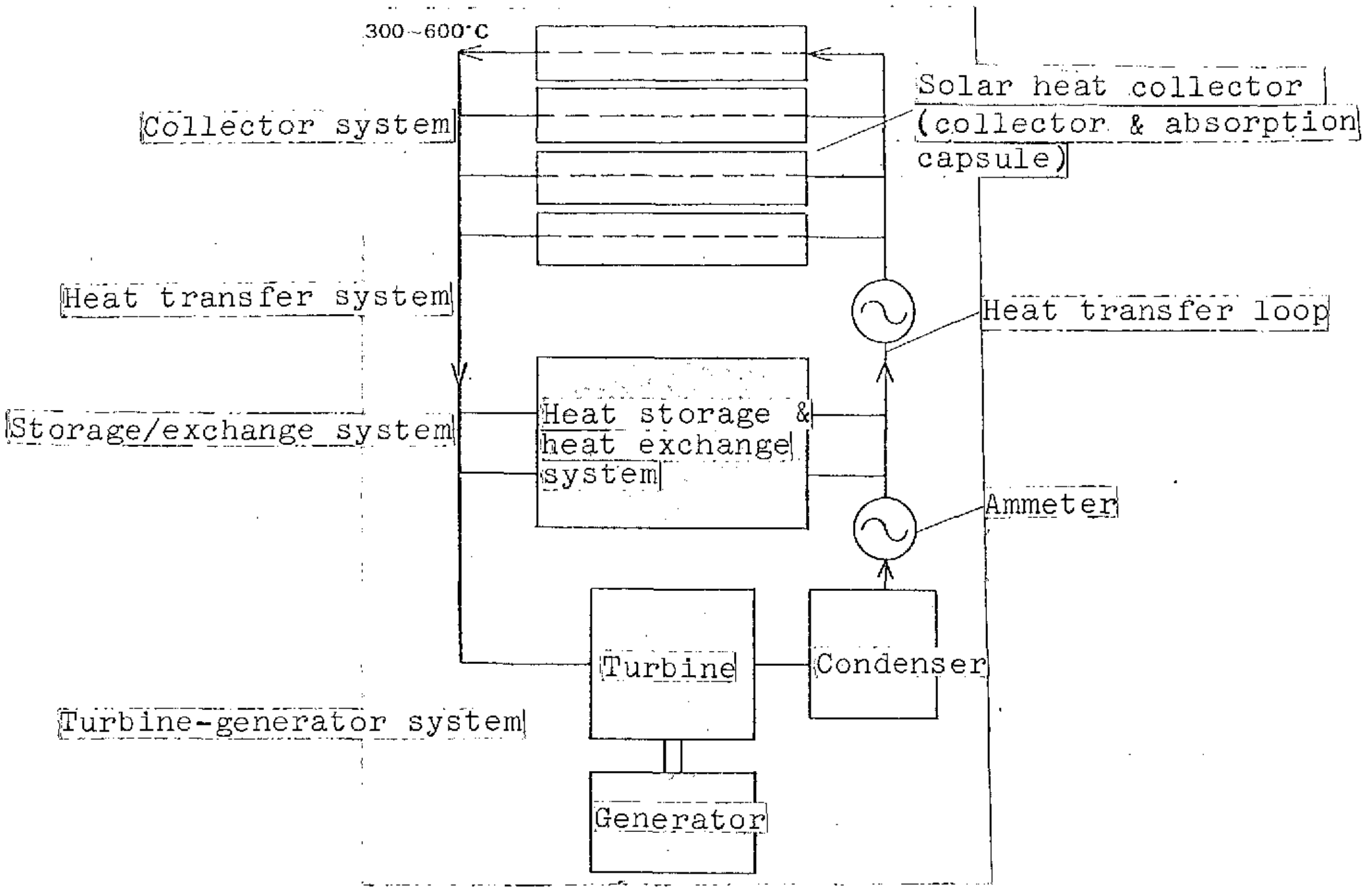
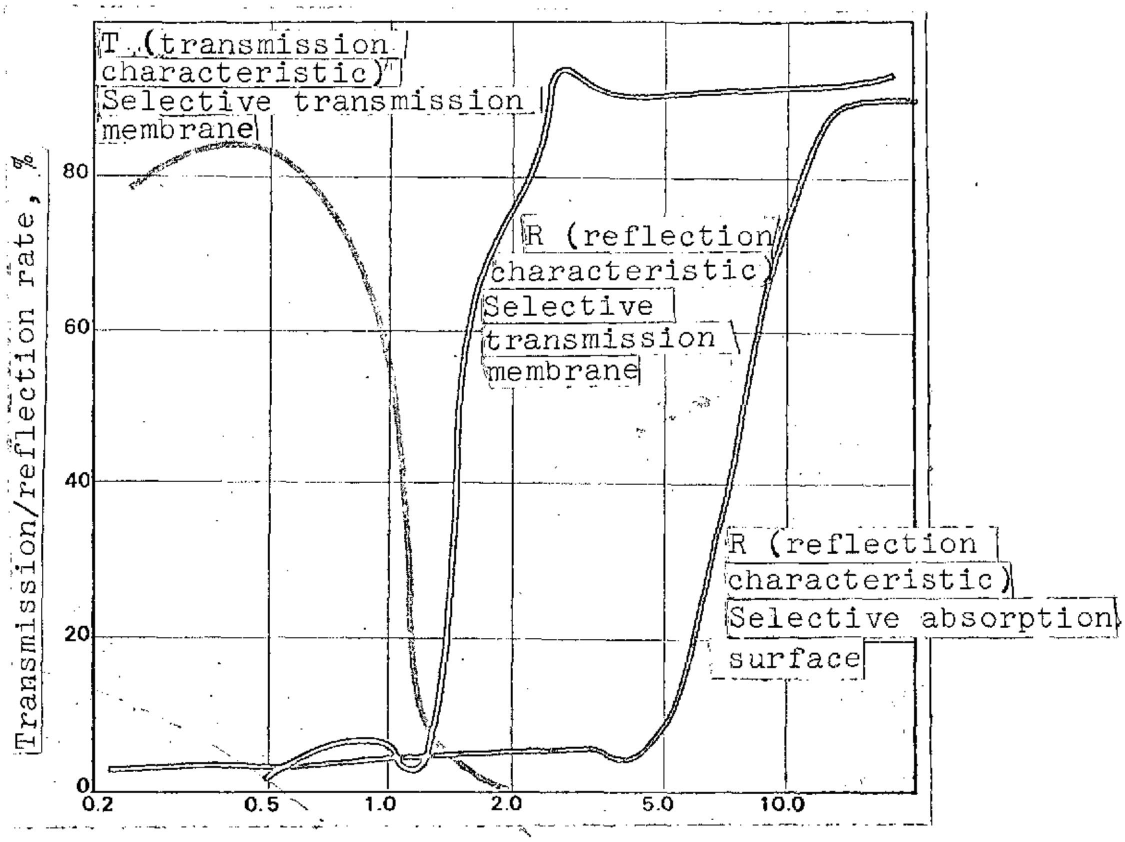



Figure 3. Solar heat power system. Solar heat power system is composed of the heat collector system, heat transfer system, storage and exchange system and generator system

absorption surface on the absorber can transmit and absorb the solar energy over the entire frequency range of visible light. Solar energy distribution is highest over the range of visible light. Once it reaches the capsule, solar heat is sealed in without being radiated. /51

Figure 4 shows the characteristic curves of the selective transmission membrane and selective absorption surface. The efficiency of the absorption capsule in the solar furnace No. 1 is 65% in absorbing and converting solar energy, and the highest temperature obtained in 425° C. For the solar furnace No. 2, we are expecting 80% efficiency, and a maximum temperature of 500 - 600° C.

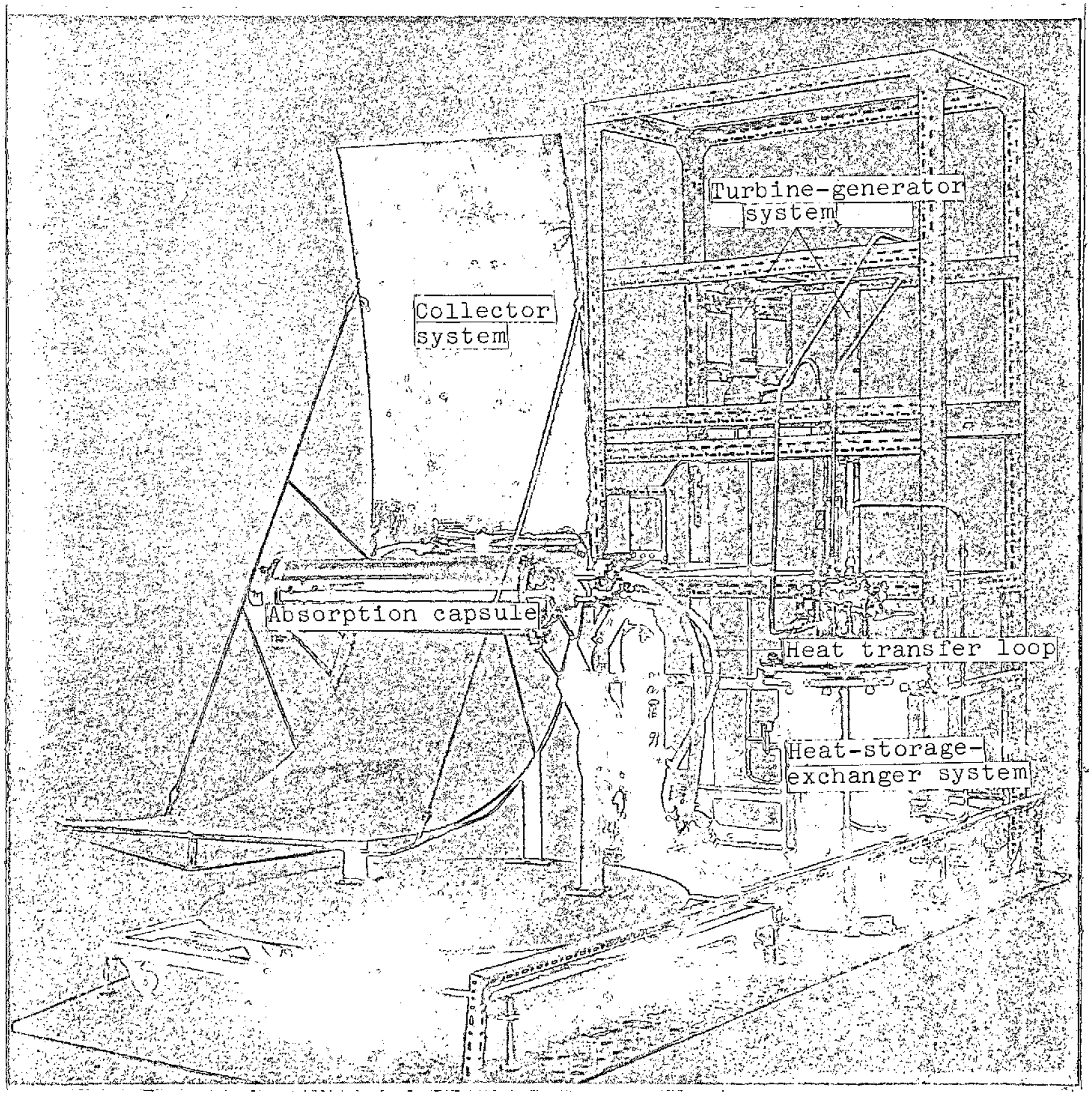



Wavelength λ (μm)

Figure 4. Characteristic curves of selective transmission and absorption. Solar energy distribution has its peak at 0.5 μm. This membrane and surface transmit and absorb all energy spectra over the range of visible light. The radiation from the absorber cannot escape the capsule

The heat storage unit and exchange system contains an efficient insulation (occasionally, pressure) vessel, and a mixture with the properties of high melting point, high latent heat, and high specific heat is used as a heat storage medium. The heat capacity of this mixture is between 600 and 900 calories per cubic centimeter, and the melting point is between 150° and 850° C.

Let us consider the applicability of solar heat power systems in Japan. If we build one or two solar power stations with a four square kilometer (2 km x 2 km) collector area, we will have about 60 stations in Japan. These stations will receive $2.98 \cdot 10^{14}$ k




NOT REPRODUCIBLE

Figure 5. Model solar power system

The photograph shows the model solar power system which was built experimentally by the authors. The absorption capsule is placed at the focus of the parabolic mirror and the collected solar energy [collection rate (the ratio of the opening distance of the parabolic surface to the radius of the absorber) : 65] is sealed into the capsule as thermal energy.

calories of solar energy annually. Assuming 30% efficiency, it will /52
be equivalent to $8.94 \cdot 10^{13}$ k calories ($1.04 \cdot 10^{11}$ kWh), amounting to one-third of Japan's total electric power requirements of $3.46 \times 10^{11}$ kilowatts in 1973. The construction cost of the solar power system is estimated at \$400 - \$677 per kW. The solar heat power system will be fully established only when the technical problems of building the high efficiency absorber-converter, storage-transfer system, optimal design of generator system, cost reduction, and environmental effects are all solved.

When 2000 - 3000° C heat sources can be easily obtained, we can think of solar heat-thermal electronic power systems, and also the manufacture of hydrogen gases by pyrolyzing water.

Next let us consider solar light power systems. Presently, we can consider two kinds: the Earth-based power station and the space power station. The latter is preferred over the former, because in outer space more room is available for solar cell arrays, and the intensity of solar energy is 15 times stronger than on the ground, and there is no day and night cycle or seasonal or weather variations.

However, there are the disadvantages of launching and controlling satellites, and the need for wireless power transmission. For each system, the most important thing is to develop high-efficiency low-cost solar cells.

At present, Si solar cells are widely used. Their energy conversion efficiency is 10%. Theoretically, InP, GaAs, CdTe are better materials for solar cells, but there are various problems, such as scarcity of raw materials and technical problems. There are also problems of poor weather resistance, pollution from production processes, etc., regarding all the materials, including Cd solar cells. /53

According to a recent report, a heterojunction solar cell based on GaAs achieved 18% efficiency using multistage junctions. We are expecting a good result from this heterojunction technique, which has been just introduced in industry.

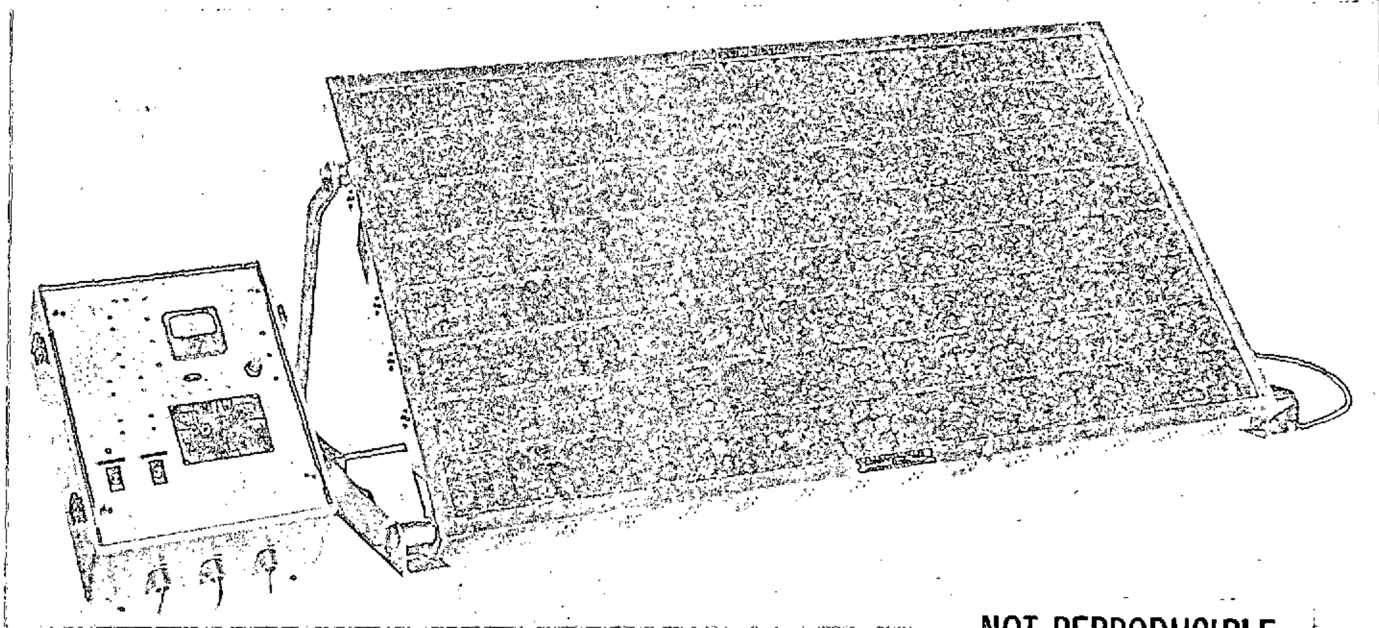


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Figure 6.) Solar cell array. Solar cell converts solar energy to electric power. This array contains more than 1000Si solar cells. 27 Si solar cell is capable of generating 1 watt of power; as a whole, 40 watts is generated. Distribution panel is at the left (picture supplied by Japan Electric Co., Inc.)

At present, the cost per kW of a solar cell power system is about $100,000, far exceeding the corresponding costs of the thermal or nuclear power station (about $200 per Kw), and, therefore cost reduction is particularly desirable.

Up to the present, solar cells on the ground have had a small capacity, being used only for special applications. In the future, they will be used as power sources built into houses and buildings. With the progress in technical developments, solar cell power stations will function as small and medium sized power stations on the ground to supply electric power to the users in the same way as any other conventional power source.

Recently in Russia, France, and the U.S.A., on-ground solar light power systems based on the light collimation method have been planned. These systems are to concentrate solar energy by 6 - 10 times, and generate one to several thousands kW of power. These systems will become the first large scale solar light power systems on the ground, and therefore their results are of great interest.

In space solar power systems, power will be generated by solar cell arrays placed on space stations, and power will be transmitted to the ground by microwave beams. A typical project of this sort is the one by NASA on a mammoth scale. It is called SSPSC (Satellite Solar Power System). According to the plan, a satellite power station will be boosted into a fixed orbit at a distance of 350,000 km from the ground, and 3 - 15 million kW of power will be generated by solar cells (see Figure 6). A microwave power beam will be used for power transmission. The solar cell array will consist of two modules, each 4.95 x 5.2 km in size. The diameter of the power transmitter antenna will be 1 km. Transmitted power will be received by an antenna 7.2 km in diameter on the ground, and then the frequency will be transformed to the commercial power frequency.

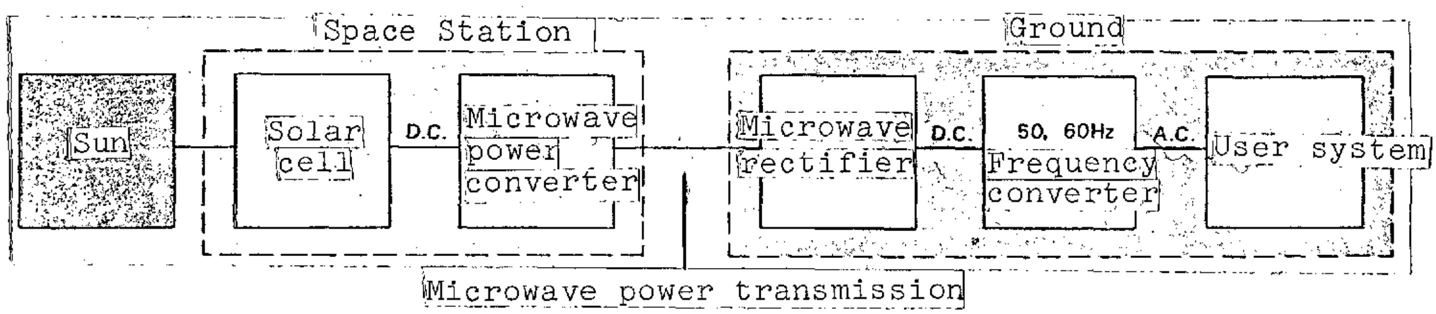


Figure 7. Space power system. The representative project is by NASA. In space, the power station is not affected by weather or seasonal changes, etc. Regarding this system, see p. 130 (Energy Conversion and its Efficiency, by C. M. Summers)

The construction cost of a prototype space power station is estimated between $1200 and $1300 per kW. Since there is no cost for fuel, it can compete with the existing power systems.

As a way of further improvement of a solar cell power station, we can lower the cost of Si solar cells by a factor of one hundred, and raise the cell efficiency.

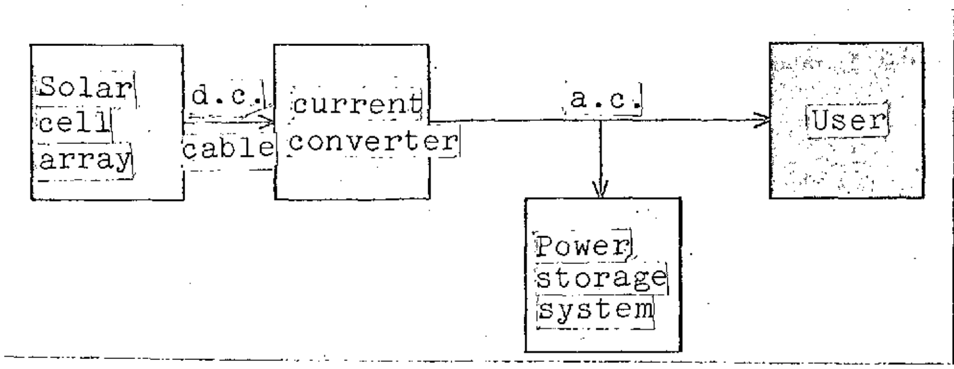


Figure 8. Solar cell power system on the ground. With the progress of solar cell technology and other necessary techniques, small and medium size power stations will appear soon

There are numerous tasks and problems to be studied, such as research and development of large scale substations, optimization of microwave frequency, estimation of power loss during transmission, ecologically safe transmission, density, and interference with wireless communications.

Up to this point we have presented the present situations and prospects for solar energy utilization. Recent requests for solar energy utilization from various fields originated because of the crisis related to the exhaustion of fossil fuel and environmental deterioration. However, solar energy will become a practical energy source only thanks to recent scientific and technological progress.

Advances have been made in high-temperature measurement techniques, materials for high efficiency selective absorption/transmission surfaces, high temperature heat pipes, heat storage media for solar heat power systems, and semiconductor techniques, plus space technology for solar cell power systems. These developments are not yet completed; only various breakthroughs have been achieved in each field of study. As a result of this progress, solar energy began to appear in practical applications such as heating-air-conditioning power stations, and manufacture of hydrogen gas.

In the future, hydrogen gas can be manufactured directly from water, using solar energy and semiconductor techniques. Also, the photosynthesis of organic fuel and protein by artificial photosynthesis will become possible in the laboratory.

However, solar energy has not only merits, but also faults, which must be overcome by technical progress. In order to secure a bright future for solar energy utilization, it is indispensable to set up a strong research and development project based on long term plans, and to concentrate all of our efforts in this direction.